Géographie physique et Quaternaire

The Fluvial Reworking of Late Pleistocene Drift, Squamish River Drainage Basin, Southwestern British Colombia

Le remaniement fluviatile des dépôts glaciaires du Pléistocène supérieur dans le bassin versant de la Squamish River, au sud-ouest de la Colombie-Britannique

Die fluviatile Umgestaltung glazialer Ablagerungen des späten Pleistozan, Emahrüngsbecken des Squamish River, südwestliches British Columbia

Gregory R. Brooks

Volume 48, numéro 1, 1994

URI : https://id.erudit.org/iderudit/032972ar
DOI : https://doi.org/10.7202/032972ar

Aller au sommaire du numéro

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Découvrir la revue

Citer cet article

Brooks, G. R. (1994). The Fluvial Reworking of Late Pleistocene Drift, Squamish River Drainage Basin, Southwestern British Colombia. *Géographie physique et Quaternaire*, *48*(1), 51–68. https://doi.org/10.7202/032972ar

Résumé de l'article

Les sédiments glaciaires remaniés sont une composante de la sédimentation périglaciaire issue du remaniement fluviatile des dépôts glaciaires dans le paysage postglaciaire. Dans le bassin versant de la Squamish River, la principale source de sédiments glaciaires remaniés provient d'un encaissement fluvial dans les matériaux de remblaiement des cinq principales vallées tributaires du bassin-versant. La quantité de matériaux transportée de ces vallées tributaires à la vallée Squamish est de 415 x 106m3. Les volumes impliqués à partir de chacune des vallées varient de 6 à 130 x 106m3, la morphologie de la vallée et le type d'évolution au Quaternaire supérieur étant les principaux facteurs intervenant dans les quantités exportées. Les données géomorphologiques démontrent que la plus grande partie de l'apport sédimentaire était déjà répartie dans la vallée Squamish il y a des milliers d'années, mais qu'il se poursuit à un taux résiduel dans le paysage actuel. Les dépôts glaciaires remaniés représentent une composante mineure de l'approvisionnement de sédiments postglaciaires dans la vallée de la Squamish River.

Géographie physique et Quaternaire, 1994, vol. 48, n° 1, p. 51-68, 8 fig., 4 tabl.

THE FLUVIAL REWORKING OF LATE PLEISTOCENE DRIFT, SQUAMISH RIVER DRAINAGE BASIN, SOUTHWESTERN BRITISH COLUMBIA

Gregory R. BROOKS*, Department of Geography and The Institute for Quaternary Reseach, Simon Fraser University, Burnaby, British Columbia V5A 1S6.

ABSTRACT Reworked glacial sediment(s) (RGS) represents the component of paraglacial sedimentation derived from the fluvial reworking of late Pleistocene glacial deposits in the postglacial landscape. In Squamish River drainage basin, southwestern British Columbia, the primary source of the RGS transferred to Squamish Valley is fluvial incision into valley-fill deposits in the five major tributary valleys of the watershed. The total volume of RGS transferred to Squamish Valley is $415 \times 10^6 m^3$. The volume of RGS from the individual tributary valleys range from 6 to $130 \times 10^6 m^3$ with valley morphology and late Quaternary history being the important controls upon the specific amount. Geomorphic evidence indicates that the bulk of the RGS was contributed to Squamish Valley thousands of years ago. The transfer of RGS continues at a very low residual rate in the contemporary landscape. RGS appear to represent a minor portion of the Squamish valley-fill and a small component of the postglacial sediments stored in Squamish Valley.

RÉSUMÉ *Le remaniement fluviatile des dépôts glaciaires du Pléistocène supérieur dans le bassin versant de la Squamish River, au sud-ouest de la Colombie-Britannique.* Les sédiments glaciaires remaniés sont une composante de la sédimentation périglaciaire issue du remaniement fluviatile des dépôts glaciaires dans le paysage postglaciaire. Dans le bassin versant de la Squamish River, la principale source de sédiments glaciaires remaniés provient d'un encaissement fluvial dans les matériaux de remblaiement des cinq principales vallées tributaires du bassin-versant. La quantité de matériaux transportée de ces vallées tributaires à la vallée Squamish est de $415 \times 10^6 m^3$. Les volumes impliqués à partir de chacune des vallées varient de 6 à $130 \times 10^6 m^3$, la morphologie de la vallée et le type d'évolution au Quaternaire supérieur étant les principaux facteurs intervenant dans les quantités exportées. Les données géomorphologiques démontrent que la plus grande partie de l'apport sédimentaire était déjà répartie dans la vallée Squamish il y a des milliers d'années, mais qu'il se poursuit à un taux résiduel dans le paysage actuel. Les dépôts glaciaires remaniés représentent une composante mineure de l'approvisionnement de sédiments postglaciaires dans la vallée de la Squamish River.

ZUSAMMENFASSUNG *Die fluviatile Umgestaltung glazialer Ablagerungen des späten Pleistozän, Ernährungsbecken des Squamish River, südwestliches British Columbia.* Umgestaltete glaziale Sedimente sind ein Bestandteil der paraglazialen Sedimentierung, die aus der fluviatilen Umgestaltung glazialer Ablagerungen des späten Pleistozäns in der postglazialen Landschaft hervorgegangen ist. Im Ernahrungsbecken des Squamish River, südwestliches British Columbia, ist die Hauptquelle der zum Squamish-Tal transportierten umgearbeiteten glazialen Sedimente fluviatiles Einschneiden in die Talaufschüttungsablagerungen in den fünf wichtigsten Nebentälern des Flussbeckens. Das gesamte Volumen der zum Squamish-Tal transportierten umgestalteten glazialen Sedimente beträgt $415 \times 10^6 m^3$. Das Volumen des Materials von den einzelnen Nebentälern reicht von 6 bis $130 \times 10^6 m^3$, wobei Talmorphologie und Geschichte im späten Quaternär die wichtigen Kontrollfaktoren für die jeweilige Menge darstellen. Geomorphologische Daten zeigen, dass der grösste Teil der umgestalteten glazialen Ablagerungen schon vor mehreren tausend Jahren im Squamish-Tal verteilt war. Der Transport dieses Materials setzt sich in der gegenwärtigen Landschaft in einer sehr niedrigen Rückstandsrate fort. Umgestaltete glaziale Sedimente scheinen einen geringfügigen Teil der Squamish-Talauffüllung auszumachen und sind ein kleiner Bestandteil der im Squamish-Tal gelagerten postglazialen Sedimente.

Manuscrit reçu le 3 septembre 1992; manuscrit révisé accepté le 25 juin 1993

* Present address: Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8

INTRODUCTION

In the Canadian Cordillera during the waning of the Fraser Glaciation, vast quantities of sediment were available to fluvial systems. The late Quaternary stratigraphic record shows thick sequences of glacio-lacustrine and glacio-fluvial deposits accumulating in valley bottoms (Clague, 1986). The sediments carried by rivers during this time were derived primarily from proglacial sources and from the reworking of glacial deposits left behind by the ice (Church and Ryder, 1972). The proglacial component is contributed directly by the ice and is contingent upon the existence of glaciers in the landscape. The "reworked glacial" component will persist into the postglacial period[1], but is dependent upon a finite source of glacial deposits which eventually will become exhausted (Church and Ryder, 1972). Thus, it will decrease over time as supplies of easily erodible glacial deposits wane or become inaccessible to the stream network and as the land surface becomes stabilized by a vegetation cover.

The combined proglacial and reworked glacial components produce fluvial sedimentation rates that initially are very high during deglaciation and decrease gradually into the postglacial period as the ice wanes and easily erodible glacial deposits become depleted. Eventually, the sedimentation rates will stabilize and begin to reflect "normal" postglacial denudation in the landscape. The high proglacial sediment supply during deglaciation and the reworked glacial component are direct products of glaciation and represent a temporary supplement to "normal" postglacial denudational processes. Church and Ryder (1972) have termed the high fluvial sedimentation rates conditioned by glaciation as "paraglacial sedimentation", and the time span over which it occurs as the "paraglacial period". The paraglacial sedimentation model has been invoked to explain the formation of now inactive alluvial fans in the landscape which formed during the early postglacial period (*e.g.,* Ryder, 1971a, 1971b; Church and Ryder, 1972; Ritter and Ten Brink, 1986; Eyles and Kocsis, 1988; Jackson, 1987) and the early postglacial aggradation of river valleys by fluvial deposits (*e.g.*, Jackson *et al.*, 1982).

Although paraglacial sedimentation relating to the Fraser Glaciation is often cited as an important component of postglacial sedimentation to rivers in the Cordillera (*e.g.*, Clague, 1981; Ryder and Clague, 1989; Day, 1989), it has been the subject of very little direct research. This paper examines the reworked glacial component of paraglacial sedimentation derived from late Pleistocene drift in Squamish River drainage basin, southwestern British Columbia (Fig. 1). It is the reworked glacial component that extends the interval of paraglacial sedimentation into the postglacial period and may have an important role in conditioning the morphology of contemporary river systems. Specifically, the paper investigates the volume of reworked glacial sediment(s) (RGS) delivered to the trunk valley of Squamish River drainage basin and the timing of this sediment transfer. This volume is assessed in terms of its contribution to the valley-fill deposits stored within Squamish Valley.

1. The terms *postglacial, deglacial* and *glacial* are used throughout this paper to refer to intervals of time in the history of a river system. Precisely defining these periods is difficult, however, because they are conceptual in nature and diachronous in application. With respect to an individual drainage system, the terms here generally imply the following: the *glacial period* refers to the time of ice coverage; the *deglacial period* applies to the interval of active retreat of the glaciers and the *postglacial period* refers to the time after the complete withdrawal of the ice or the attainment of its restricted contemporary position(s) within the landscape.

PARAGLACIAL SEDIMENTATION

As outlined above, the notion of paraglacial sedimentation is relatively straightforward for a watershed that was totally deglaciated; sedimentation rates decrease and eventually reflect "normal" postglacial denudation. The persistence of glaciers in the alpine areas of many Cordilleran drainage basins (such as the Squamish River study area), however, complicates the definition of paraglacial sedimentation because glaciers have influenced fluvial sedimentation throughout the entire postglacial period (see Eyles and Kocsis, 1988; Church and Ryder, 1989; Eyles and Kocsis, 1989). In such a setting, alpine glaciers have introduced proglacial sediments into the river system continuously over the postglacial period so that the proglacial component, and thus paraglacial sedimentation, has not ceased. These glaciers have not remained static in extent; postglacial climatic change has produced several Neoglacial phases (*e.g.*, Duford and Osborne, 1978; Luckman and Osborne, 1979; Ryder and Thomson, 1986; Ryder, 1987; Desloges and Ryder, 1990) to which the proglacial component probably responds proportionally. A Neoglacial retreat exposes fresh drift within the areas of the drainage basin that were overridden by the recent advance thus causing the rejuvenation of the reworked glacial component. Neoglacial fluctuations can produce discrete surges in the postglacial fluvial sedimentation rates that are detectable in the geomorphic record (*e.g.*, Leonard, 1985; 1986a; 1986b) and which can have morphologic effects upon Cordilleran river systems (*e.g.*, Ryder, 1981; Church, 1983).

With respect to the late Quaternary timescale, there is a significant difference between paraglacial sedimentation arising from the immediate waning of the Fraser Glaciation and that persisting from the continued presence of alpine glaciers, although the specific processes concerned are identical. In general within a given drainage basin, the ice cover during the Fraser Glaciation was much more extensive than during the Neoglacial advances and therefore likely produced a far greater supplement to fluvial sedimentation (see Clague, 1986). Also, paraglacial sedimentation relating to the Fraser Glaciation was generated during a transition of a glacially dominated landscape to a fluvially dominated landscape. Neoglacial fluctuations, in general, are restricted to areas immediately proximal to the postglacial ice fields with the majority of the landscape being unaffected. Finally, continued paraglacial sedimentation in the postglacial period relates to the enduring presence of ice fields in the landscape — albeit, subject to climatically induced fluctuations — not to the large scale deglaciation of the landscape.

In this study, paraglacial sedimentation arising from the waning of the Fraser Glaciation is defined as occurring within

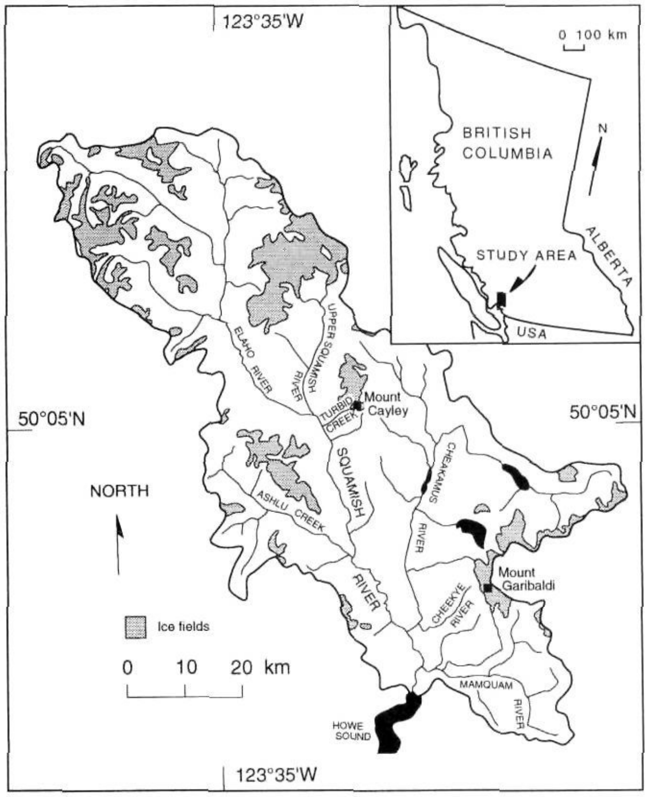

FIGURE 1. Squamish River drainage basin, southwestern British Columbia.

Le bassin-versant de la Squamish River, en Colombie-Britannique.

a "transitional" paraglacial period to emphasize that it relates to the transition from a glacially to fluvially dominated landscape. Paraglacial sedimentation perpetuated by postglacial ice fields occurs within a "persistent" paraglacial period indicating that it is associated with a continued glacial presence. The shift from the transitional to persistent paraglacial period occurs when the proglacial component of sedimentation begins to reflect the extent of the postglacial ice fields (since the proglacial component never ceases) and the reworking of late Pleistocene drift wanes; *i.e.*, fluvial sedimentation reflects only "normal" postglacial denudation of the landscape — including the contribution from the postglacial ice fields. Since the proglacial component may reflect the extent of the postglacial ice fields long before the reworking of late Pleistocene drift wanes, the transitional and persistent paraglacial periods are, in a sense, superimposed upon one another. Because of Neoglacial fluctuations, sediment supply from the postglacial ice fields probably has not been constant, causing secondary paraglacial episodes to be superimposed upon the transitional and/or persistent paraglacial periods.

The conceptual difference between transitional and persistent paraglacial periods must be recognized when investigating paraglacial sedimentation in any watershed containing contemporary ice fields. In the present landscape, the proglacial component should reflect the extent of the contemporary ice fields and there may be some reworking of Neoglacial drift, but the reworking of late Pleistocene drift may or may not be an important source of sediment.

This paper is concerned with only the reworked glacial component arising from a transitional paraglacial period, *i.e.*, the fluvial reworking of Fraser Glaciation drift.

STUDY AREA

Squamish River drainage basin occupies an area of 3600 km^2 that extends northward into the southern Coast Mountains from the head of Howe Sound, a fjord located in southwestern British Columbia (Fig. 1). Local geology consists primarily of diorite, granodiorite and quartz diorite plutons with minor occurrences of metamorphic rocks, all of Jurassic-Cretaceous age and typical of the Coast Plutonic Complex (Roddick *et al.*, 1979). Quaternary rocks of the Garibaldi Volcanic Belt extend discontinuously across the drainage basin in a roughly north-northwest direction from the head of Howe Sound (Green *et al.*, 1988). The local mountains range in elevation from 1500-2000 m with the higher peaks reaching 3000 m. Partitioning the mountains are deep U-shaped valleys reflecting the former presence of glaciers, most recently during the Fraser Glaciation. At the height of this glaciation (14.5-14 ka BP; Ryder and Clague, 1989), the mountain landscape was covered by an ice sheet with only the higher peaks protruding (Ryder, 1981). A valley glacier occupied Squamish Valley and much of Howe Sound until at least 11.3 ka BP (Mathews *et al.*, 1970; Armstrong, 1981), while in the southern Coast Mountains deglaciation was finished before 9.5 ka BP (Ryder and Thomson, 1986) when ice retreated to its present alpine position (Fig. 1). At present, alpine glaciers cover about 11% of the drainage basin.

As a result of this glaciation, the land was depressed isostatically causing high relative sea levels during deglaciation and into the postglacial period. A sea level curve does not exist for Howe Sound, but those of the nearby Fraser Lowland indicate that coastal areas were inundated up to about the present 200 m contour at 13 ka BP (Mathews *et al.*, 1970; Clague *et al.*, 1982). Rapid uplift caused sea level to fall, reaching its postglacial minimum of -12 m asl by 9 ka BP. Sea level then rose, gradually reaching its present position by 5 ka BP and has remained sensibly constant ever since (Clague *et al.*, 1982; Williams and Roberts, 1989). The extent of inundation in Squamish Valley is not known, but it appears that much of Squamish Valley was still occupied by glaciers when sea level in the Fraser Lowland was at its highest position. A raised delta deposit at the mouth of Mamquam Valley, however, at least partially relates to this inundation. It is not known if differential isostatic uplift has caused significant tilting of the drainage basin.

Squamish River network exhibits a trellis drainage pattern, the general alignment of which reflects bedrock structure, joints and faults within the Coast Plutonic Complex (Holland, 1964). Branching from the trunk valley are five major tributary valleys, occupied by Ashlu Creek and Cheakamus, Elaho, Mamquam and "upper" Squamish rivers, (Fig. 1). For the purposes of discussion, Squamish River and Squamish Valley are considered to extend from Squamish delta at the head of Howe Sound to the Squamish-Elaho confluence. Above this confluence, the river will be referred to as "upper" Squamish River flowing in "upper" Squamish Valley; the latter being regarded as a major tributary valley to Squamish Valley.

The planform of the gravel-bed Squamish River ranges from braided over the initial 28 km to meandering for the remaining 28 km to Squamish delta (see Brierley, 1989). Along its course, the river flows upon an intact (unincised) valley-fill deposit extending from about the Elaho-Squamish confluence to Squamish delta. A minor exception to this occurs along the western base of Mount Cayley where the river is incised into debris avalanche deposits that form the Turbid Creek debris fan located at the mouth of Turbid Creek (Fig. 1; see Evans and Brooks, 1991). The valley-fill is contained by the steep bedrock sides of Squamish Valley and is isolated from other alluvial reaches within the watershed by bedrock canyons occurring at or a short distance above the mouths of the major tributary valleys. The fill receives sediment from the upstream areas of the stream network and is gradually extending into Howe Sound through delta progradation (see Hickin, 1989). The valley-fill (hereafter referred to as Squamish valley-fill) represents the long-term storage within the drainage basin of sediments that have been carried through the stream network.

RESEARCH APPROACH

The RGS delivered into Squamish Valley undoubtedly are stored within Squamish valley-fill, but discriminating them from sediments of other origin (postglacial, Fraser Glaciation and possibly pre-Fraser Glaciation) probably is impossible. An alternative approach is to focus upon the source areas of RGS. Since RGS were derived from the erosion of pre-existing glacial deposits, remnants of those deposits should remain in the landscape. The morphology of these remnant deposits, together with the age of their erosion, should allow the volume of RGS stored in Squamish Valley and the time period over which they were transferred to be determined. The obvious assumption in this approach is that some trace of the eroded glacial deposits still remains in the landscape. Uneroded glacial deposits, thus, are interpreted to indicate that little RGS has been derived from an area. A similar interpretation applies to an area completely devoid of glacial deposits (*e.g.*, a barren bedrock valley). Rejection of this assumption implies that virtually any quantity of glacial material may have been removed without leaving any geomorphic evidence of the event in the source area(s) — a most unlikely circumstance. All observations and conclusions of this study concerning the reworked glacial component are based upon the visible evidence of erosion in the landscape.

At the drainage basin scale, the most likely source areas of RGS are the major tributary valleys and the sides of the Squamish Valley. However, little RGS appears to have been derived from the sides of Squamish Valley since they are very steep and consist primarily of bare rock. In contrast, reconnaissance revealed extensive eroded glacial deposits along the valley bottoms of the major tributary valleys (see below). This investigation of the reworked glacial component, therefore, focused upon the geomorphology of the major tributary valleys.

To appraise the reworked glacial component, the specific sources of the RGS in the major tributary valleys must be established. RGS are derived from the erosion of glacial deposits, but since the major tributary valleys are relatively large (290-1250 km^2), inevitably some of this material will be removed from one area of a tributary valley and stored in another. Such a movement results in the "within-valley" storage of sediment rather than its export to Squamish Valley unless the secondary feature itself subsequently becomes eroded. That is, not all eroded glacial deposits have been transferred to Squamish Valley. The field procedures, therefore, examine only remnant glacial deposits in the major tributary valleys from which sediments have been exported to Squamish Valley.

The major surficial geologic units of the principal tributary valleys and their relative contribution to the RGS exported to Squamish Valley are listed and reviewed in Table I. From this review it appears that fluvial incision into valley-fill deposits by the major streams is the largest source of exported RGS. This incision clearly has resulted in the transfer of sediment to Squamish Valley since there are no intermediate storage sites between the incised valley-fills in the tributary valleys and Squamish valley-fill. Certainly some RGS has been derived from other surficial geologic units, particularly those of the valley-sides, but these primarily appear to have been stored within-valley at the base of the slopes in fans or aprons, and along the valley bottoms as valley-fill. While some of this material subsequently has been further reworked and exported, the volume derived from the fans and aprons appears to be small relative to that of the incised valley-fill. The valley-side contribution may be partially reflected by the valley-fill incision since the within-valley storage of these sediments may have contributed to the initial aggradation of the valley-fill. The methodology, therefore, focuses upon measuring the volume of incision into the valley-fill and the dating of erosional terraces.

It is possible, however, that major aggradational episodes unrelated to the transitional paraglacial period have formed terraces along the valley bottom(s) thereby complicating the notion that the volume of valley-fill incision reflects the amount of RGS stored in Squamish Valley. To demonstrate that the terraces are glacial or at least late Pleistocene glacial deposits, brief descriptions of the valley-fill composition are included below. A comprehensive inventory of the valley-fill stratigraphies is not available although more information, including numerous stratigraphic sections, is contained in Brooks (1992).

METHODOLOGY

The elevation of major and minor terraces, breaks-in-slope and the water surface were measured along regularly spaced "cross-valley profiles" extending from the valley-fill terrace (highest terrace) to the stream along one side of the lower valley. Cross-valley profiles were surveyed every 0.5 to 2 km as necessary to depict the valley bottom morphology and along both sides of the valley where accessible. Most cross-valley profiles were mapped on aerial photographs of

TABLE I

Qualitative assessment of major surficial geologic units in the major tributary valleys and their relative contribution of RGS exported to Squamish Valley

Surficial geoloic unit	Description	Location	Comment and assessment
Bare rock	– barren bedrock	– widely exposed on mountain tops above tree line and also on very steep slopes of valley-sides	– probably barren since deglaciation. – believed to have made no significant contribution to exported RGS.
Drift veneer	– < 2 m thick, patchy covering of drift	– covers the majority of the valley-sides	– believed to be an essentially intact deposit that has always been thin and patchy. Certainly some material has been fluvially reworked from these areas, but likely some has been stored within-valley contributing to valley apron and valley-fill aggradation. – believed to represent a minor contribution to exported RGS.
Drift blanket	– continuous mantle of material > 1 m thick that reflects underlying topography.	– occurs sporadically on the lower quarter of moderately sloped valley-sides.	– often severely gullied by ephemeral and perennial streams that are incised to bedrock or very coarse lag. This erosion probably has contributed to aggradation of valley apron and valley-fill, and to the export of RGS. Volume of gullying is small relative to valley-fill incision. – believed to represent a minor contribution to exported RGS.
Valley apron	– thin cover of primarily fluvial and colluvial sediments.	– occurs commonly at the base of valley-sides.	– deposits believed to represent within-valley storage of sediment derived from valley-sides; essentially intact except where they have been eroded by lateral channel migration of the major streams along the valley bottoms. Valley apron deposits are considered to be an upslope extension of the valley-fill, its erosion is included within the valley-fill incision. Erosion of valley apron has contributed significantly to the export of RGS. – lack of extensive valley apron deposits throughout the major tributary valleys supports the notion that little material has been derived from the valley-sides.
Rock avalanches	– debris generated by large scale slope failures.	– several identified in the major tributary valleys forming isolated deposits.	– all less than 10^7 m^3 with the amount of fluvial reworking considerably less. The deposits are postglacial in origin and related to "normal" denudational processes. Not relevant to the export of RGS.
Talus	– debris generated by small scale rockfalls	– common throughout major tributary valleys at the base of vertical and near-vertical slopes.	– deposits are postglacial in origin representing the within-valley storage of "normal" denudational processes. Not relevant to the export of RGS.
Colluvial fans and cones	– debris accumulations formed at the break-in-slope along the margins of the valley bottom.	– common at the base of avalanche tracks and debris flow torrents throughout major tributary valleys.	– deposits are postglacial in origin, intact and aggrading. Very minor contribution to the export of RGS.
Alluvial fans	– consist of fluvial sediments with some debris flow deposits. – *two basic types of morphology* : 1) fans incised deeply to bedrock or very coarse lag. 2) fans that are unincised and probably aggrading.	– both types of fans commonly are found throughout the major tributary valleys at the mouths of the major alpine creeks draining glaciers or névé. – incised fans generally occur along reaches where controlling base level has fallen. – unincised fans generally have formed along reaches where controlling base level has been stable or risen.	– deposits of incised fans are believed to have accumulated during deglaciation. Incision into these fans has contributed to the export of RGS, but volume is small relative to valley-fill incision. – unincised fans represent the within-valley storage of materials. They are not considered to have contributed significantly to the export of RGS.
Valley-fill	– variable composition of glaciolacustrine, glacio-fluvial and/or ice contact deposits. Long reaches of valley-fill have been incised by major streams of tributary valleys.	– located along valley bottoms of major tributary valleys.	– deposits consist primarily of glacial deposits but also of sediments derived from valley-sides that have been stored within-valley. – incised valley-fill in combination with eroded valley apron have contributed significantly to the export of RGS. Relative amount of incision *greatly exceeds that of any other surficial geologic unit.*

1:15,000-1:20,000 scale, with a smaller number at 1:50,000-1:60,000 scale.

All elevations were obtained using a Thommen altimeter (type 3B5.01.2) accurate to ± 4 m and were made relative to geodetic benchmarks in Squamish Valley and "temporary" benchmarks established throughout the tributary valleys by repeated altimeter measurements of roadside markers. In remote areas of the study area which were accessible only by foot and therefore relatively far from any of the temporary benchmarks, the relief of the valley bottom was measured with the altimeter. These relief measurements were later converted to elevations (m asl) by estimating the water surface elevation using the contour lines on 1:50,000 scale NTS topographic maps and then adjusting the measurements accordingly.

For each valley, the terrace and water surface elevations along every profile were plotted against valley-axis distance at a vertical exaggeration of three to minimize distortion. The major surfaces were identified and correlated between profiles. A series of best-fit lines was drawn connecting the points of each major surface thereby delineating the primary levels of the remnant valley-fill. For each segment of every surface, elevation was expressed as a function of valley-axis distance producing a series of linear "elevation equations". These equations allowed the elevation of any major surface to be determined at any point along the valley bottom.

The major erosional surfaces in a tributary valley were mapped on aerial photographs and transferred using a Bausch and Lomb zoom transferscope to topographic maps that had been enlarged to a scale of about 1:18,000. Digitizing of these maps using a Talos/CalComp 622 digitizer expressed the valley bottom morphology as a series of "X" and "Y" coordinates; the "Z" coordinates of the surfaces (elevation) being obtained from the elevation equations. On a reach by reach basis, the coordinates of the various surfaces were manipulated in a spreadsheet to depict the valley bottom morphology and thereby calculate the volume of incision (see Brooks, 1992). Summation of the volumes for each reach produced the total volume of incision for each valley.

Times and rates of stream incision into the valley-fill deposits were estimated from radiocarbon ages of organic materials relevant to the vertical position of the river. These materials were obtained from valley-fill deposits and by coring peat bogs.

ERROR ASSESSMENT

The volume of RGS from each valley contains errors relating to both the field and computational procedures. Error sources are listed in Table II with an assessment of their possible contribution. Since the error associated with each factor is difficult to quantify, it is classified as being minor (± 1%), moderate (± 10%) or major (± 100%) and whether it over- or underestimates the volume.

The errors of Table II produce a range of about − 10% to + 20% deviation. Collectively, the errors are self-canceling to some degree, but probably result in an overestimation of the actual volume of incision. This positive bias was applied

TABLE II

Summary of error associated with the calculation of valley-fill incision volumes

Description of Error	Assessment of Error
In the calculations, the valley-fill surfaces were assumed to be horizontal in cross-section. In some reaches this surface is represented by breaks-in-slope along the valley-side indicating that it was concave upwards.	- minor to moderate overestimation (+ 1 to 10%)
Break-in-slope misidentified as representing valley-fill surface. Where the valley-fill surface was not readily apparent, the highest feature that appeared to represent the surface was used.	- minor to moderate overestimation (+ 1 to + 10%)
Ignored minor discontinuous terraces during the calculation of incision volumes. These surfaces represent an "extra" step in the morphology of the valley-fill.	- minor overestimation (+ 1%)
Stream incision into bedrock canyons is ignored, but over the postglacial time-scale it should be accounted for in the canyon and bedrock controlled alluvial reaches. The exact amount of bedrock incision is not known; it is included as part of the RGS volumes.	- minor to moderate overestimation (+ 1 to + 10%)
Problems of recognizing younger aggradational surfaces unrelated to the transfer of RGS to Squamish Valley. Such terraces may have formed within areas of stream incision in response to unrelated postglacial events (climatic change, Neoglacial ice fluctuations, etc.). These could be difficult to recognize because of a lack of both exposures and datable materials relevant to terrace formation. Also, erosional terraces in the study area generally are capped with fluvial deposits so that differentiating the surfaces on the basis of minor exposures of fluvial sediments is difficult. Problems arising from such terraces are not regarded as serious since terraces suspected of being aggradational in origin rarely were encountered and these were situated immediately above the contemporary water surface well below the valley-fill surface.	- minor to moderate underestimation (− 1 to + 10%)
There is altimeter error along the individual cross-valley profiles. In the field, terrace measurements were checked continuously to see that they "looked right"; certainly "real" elevation changes were being measured. The rechecking of the starting point after a profile traverse allowed the error due to atmospheric pressure fluctuations to be assessed, but minor fluctuations within the ±4 m error of altimeter did occur.	- minor under-(?) or overestimation(?) (± 1%)
There is cartographic error associated with tracing morphological boundaries on aerial photographs and superimposing boundaries on maps using the zoom transferscope.	- self canceling(?)

consciously to the volume calculations since they are based exclusively upon the valley-fill incision and ignore the erosion of other geologic units (although these likely are negligible in comparison). This -10 to $+20\%$ range represents unstated error associated with any given RGS volume; in specific cases where more extreme error is apparent, it is identified and discussed within the descriptions of an individual valley. The calculated volumes of RGS are, at worst, order of magnitude estimates reflecting the uncertainty concerning the assumption that the valley-fill incision represents the volume of RGS stored in the Squamish Valley.

RESULTS

VOLUMES OF REWORKED GLACIAL SEDIMENT

Ashlu Valley

Ashlu Valley is 290 km^2 in area and joins Squamish Valley 28 km upstream of Squamish delta (Figs. 1 and 2a). Ashlu Creek is 33 km long and alternates between bedrock canyon and alluvial reaches corresponding to general narrowing and widening of the valley bottom, respectively. The canyons locally are 20-30 m in depth with the stream generally appearing to "fit" the canyon width; the upper ends of the canyons control the baselevel of the adjoining upstream alluvial reach. The alluvial reaches have a straight to meandering planform and a coarse boulder channel bed. Pokosha and Tatlow creeks are major tributaries to Ashlu Creek (Fig. 2a); they alternately flow over coarse gravel lag and in bedrock canyons.

Beginning 28 km above the valley mouth, incised valley-fill deposits are present almost continuously along Ashlu Creek, but are absent along the lower 2 km of the valley. The valley-fill terrace is both paired and unpaired along the valley bottom with its height being variable above the stream, generally thickening at the confluences of tributary valleys and some major alpine creeks (Fig. 3). The valley-fill terrace is thickest at Pokosha Creek confluence (about 65 m) immediately before it abruptly terminates. A lower surface ("B" terrace in Fig. 4) extends downstream discontinuously for another 2 km, but it is not clear if it once extended to the valley mouth.

Along Ashlu Creek, stream incision generally has cut into the valley-fill without producing major secondary terraces above the contemporary flood plain, although along many of the alluvial reaches the stream appears to be slightly incised (about 2 m) into the flood plain. Paired and unpaired terrace surfaces occur along isolated reaches of Ashlu Creek, being most prevalent between Pokosha and Pykett Creeks where sequences of up to four terraces are found. It was not feasible to correlate the secondary terraces along the valley bottom except over short distances because of the lack of continuity and insufficient dating control.

The composition of the valley-fill deposits in Ashlu Valley is complex and variable. Along the valley bottom, there are four occurrences of glacio-lacustrine deposits separated by glacio-fluvial deposits. These deposits suggest the existence of up to four separate glacial lakes, probably impounded behind ice dams or alluvial fan obstructions that were situated at the confluences of Pokosha, Tatlow, 20.5 km and 25.5 km creeks (Figs. 2a and 3). While these lake deposits have not been investigated in great detail, they are late Pleistocene in age and represent a significant amount of the valley-fill deposits.

The abrupt termination of the valley-fill at Pokosha Creek confluence probably marks the former position of the downstream-most impoundment. From limited exposures, the secondary terraces between Pokosha and Pykett creek generally appear to be erosional in origin being underlain by glacio-lacustrine sediments (Fig. 4) or represent a planed surface of the bedrock. The erosional terraces are covered with a veneer of boulder lag or flood plain(?) deposits relating to either ancestral Ashlu Creek or to small creeks flowing across the terrace surfaces. "B" terrace is the only major secondary surface that can be correlated over the Pykett-Pokosha reach (Fig. 4). It extends for another 2 km downstream, where it is composed of fluvial gravels and sands in contrast to the glacio-lacustrine sands and silts upstream. Following the failure of the Pokosha Creek impoundment, it appears that Ashlu Creek stabilized at the level of "B" terrace with the downstream extension of this surface representing aggradation that was the product of incision upstream.

Incised valley-fill deposits are present along Tatlow and Pokosha valleys, but no secondary terraces were observed between the valley-fill and the stream level. The composition of the valley-fill generally is glacigenic diamicton.

The volume of valley-fill incision was calculated over 23, 3 and 4 km reaches of Ashlu, Pokosha and Tatlow creeks, respectively (Fig. 2a). Along Ashlu Creek, incision was measured beginning at about Pokosha Creek confluence, located 6 km upstream from the valley mouth (Figs. 2a and 3), where the position of the downstream-most impoundment is interpreted to have been located. Although "B" terrace extends a further 2 km, its interpreted aggradational origin beyond Pokosha Creek confluence suggests that it represents primarily within-valley sediment storage formed after the failure of the ice dam. Thus, the incision downstream of the valley-fill terrace termination has not been included in the RGS volume. The majority of this within-valley storage subsequently has been eroded by the stream as "B" terrace becomes very discontinuous; the sediment that remains in storage represents a small proportion of the valley-fill incision upstream of Pokosha Creek confluence.

The volume of RGS exported from Ashlu Valley is calculated to be $95 \times 10^6\ m^3$ (Table III), based upon 49 cross-valley profiles along Ashlu Creek, and 4 and 2 along Pokosha and Tatlow creeks, respectively.

Elaho Valley

Elaho Valley is 1250 km^2 in area and joins Squamish Valley 54 km upstream of Squamish delta (Fig. 1). Elaho River is 55 km long from its headwaters at Elaho Glacier to the Elaho-Squamish confluence (Fig. 2b). The river flows within bedrock canyons over its upper 24 km and lower 8 km; the intermediate reach is alluvial being initially braided-wandering for 11 km then meandering for the remaining 12 km. Along the alluvial reach, Elaho River has a gravel bed with sand commonly occurring on the surface of the river bars

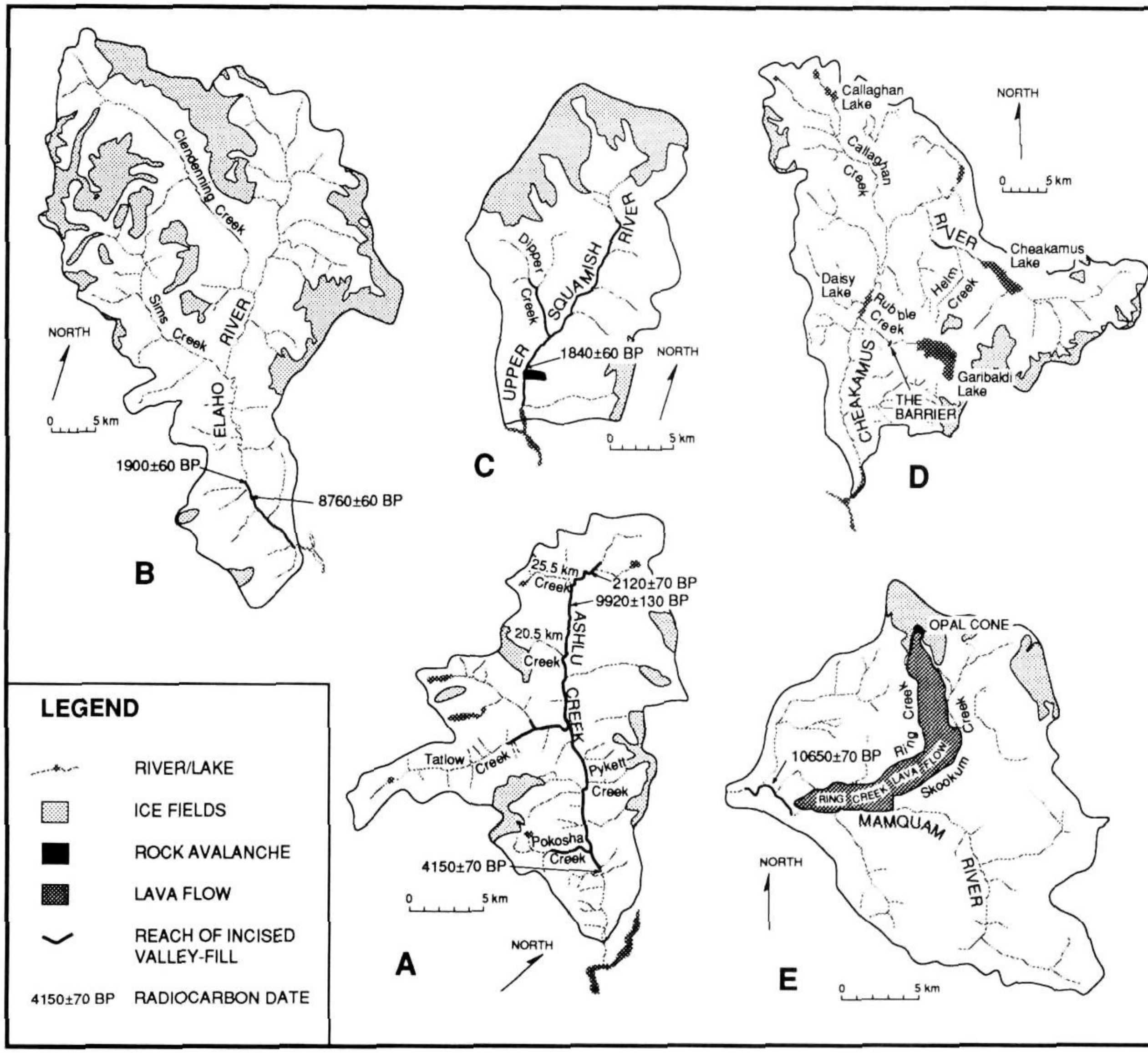

FIGURE 2. The five major tributary valleys of the Squamish River drainage basin: a) Ashlu, b) Elaho, c) upper Squamish, d) Cheakamus, e) Mamquam. Shown also are the incised reaches of valley-fill and the location of the radiocarbon dates.

Les cinq principales vallées tributaires du bassin de la Squamish River: a) Ashlu, b) Elaho, c) Squamish supérieur, d) Cheakamus, e) Mamquam. On y voit aussi les sections encaissées dans les matériaux de remblaiement et la localisation des sites de datation au radiocarbone.

TABLE III

Volume of RGS exported from major tributary valleys to Squamish Valley

Major tributary valley	Drainage basin area (km^2)	Volume (m^3)
Ashlu	290	95×10^6
Cheakamus	1100	54×10^6
Elaho	1250	6×10^6
Mamquam	360	130×10^6
upper Squamish	350	130×10^6
TOTAL		415×10^6

and in the flood plain deposits. Sims and Clendenning creeks flow are major tributaries; both have large ice fields in their headwaters (Fig. 2b).

Incised valley-fill deposits occur only along the bedrock canyon of the lower 8 km of Elaho Valley (Fig. 2b). Upstream, the river flows over intact valley-fill deposits along the alluvial reach. There is no evidence of remnant valley-fills within Sims and Clendenning valleys and along the upper canyon reach of Elaho River.

Over the 23 km long alluvial reach above the lower canyon, the morphology of the valley bottom generally consists of flood plain deposits extending from one side of the valley to the other. Unincised alluvial fans originating from the major alpine creeks are splayed partially across the valley bottom.

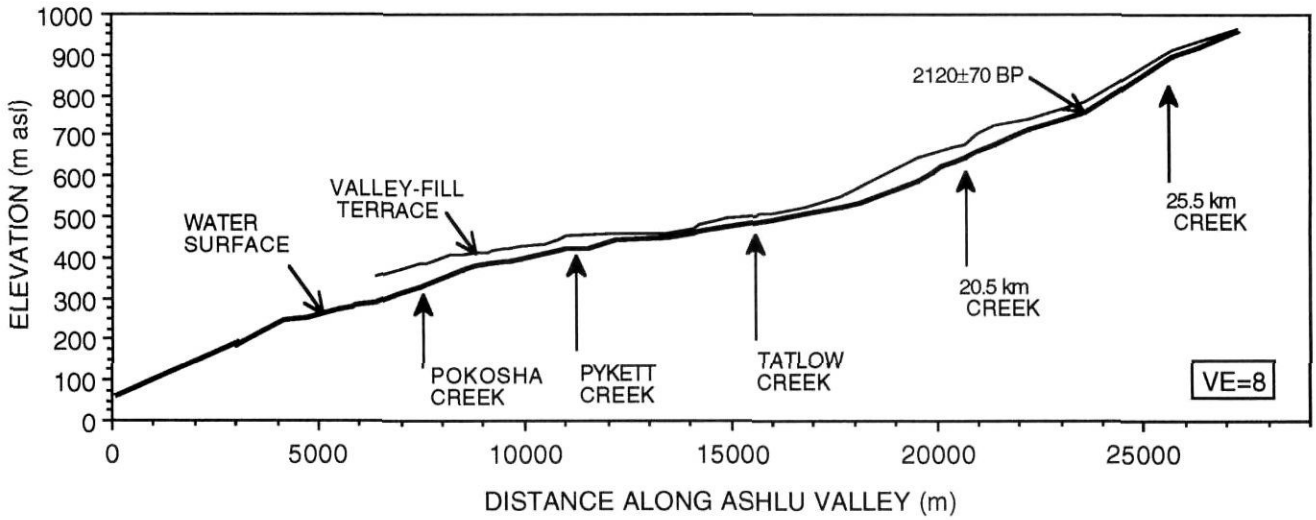

FIGURE 3. The longitudinal profile of the incised valley-fill along the Ashlu Creek: for clarity, secondary terraces are not shown. Note the vertical position of the 2120 ± 70 BP radiocarbon date between the river surface and the valley-fill terrace in the upper reach of the river.

Profil longitudinal de la section encaissée dans des matériaux de remblaiement le long du Ashlu Creek; pour plus de clarté, les terrasses secondaires ne sont pas illustrées. Noter la position verticale du site de la datation au radiocarbone de 2120 ± 70 BP entre la surface du cours d'eau et la terrasse fluviatile dans la partie supérieure.

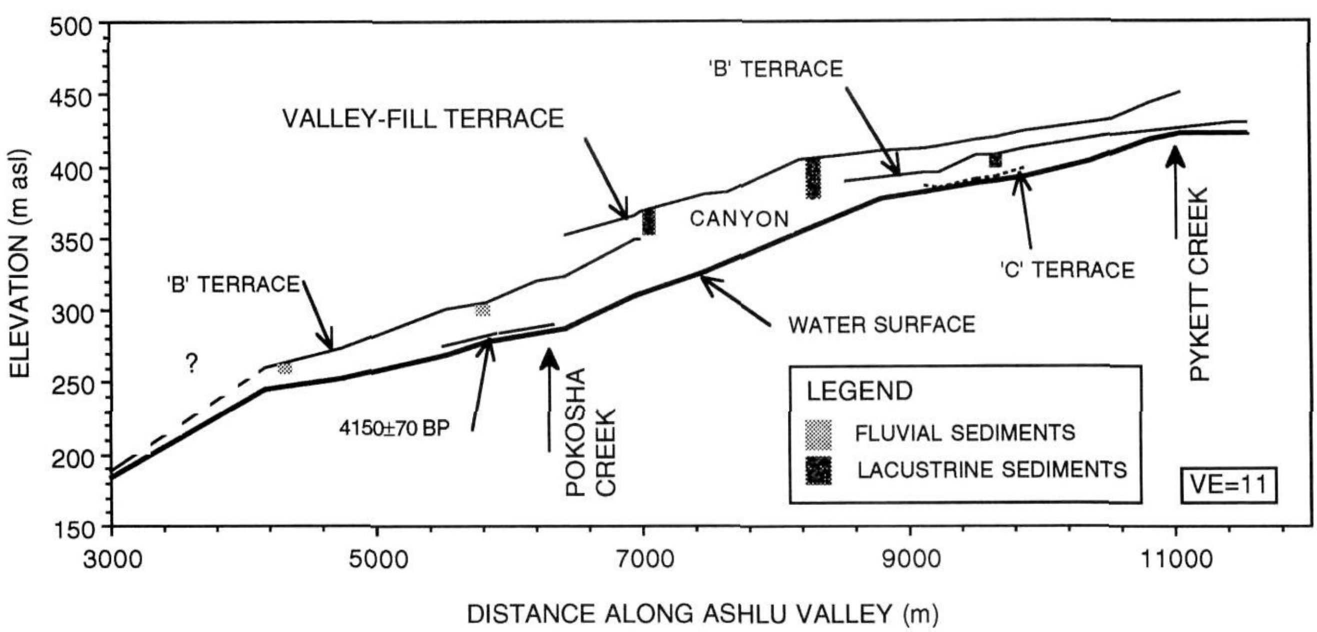

FIGURE 4. Valley-fill terrace, major secondary terraces and the water surface along Ashlu Creek in the general area of Pokosha Creek confluence. Note the vertical position of the 4150 ± 70 BP radiocarbon date in relation to the valley-fill terrace and the present water surface of Ashlu Creek.

Terrasse de remblaiement, principales terrasses secondaires et la surface du cours d'eau le long du Ashlu Creek dans la zone de la confluence du Pokosha Creek. Noter la position verticale de la datation au radiocarbone de 4150 ± 70 BP par rapport à la terrasse de remblaiement et le niveau actuel de l'eau du Ashlu Creek.

The existence of this intact valley-fill relates to the bedrock morphology of Elaho Valley. The alluvial reach appears to be situated overtop a sedimentary basin (hereafter referred to as Elaho basin) delimited by the upper end of the canyon reach immediately downstream. The subsurface profile of Elaho basin is not known, but a drill hole situated 5.25 km upstream of the canyon penetrated 37 m of "unconsolidated sand and some gravel" without reaching bedrock (BC Hydro, 1983); the bottom 8 m of this hole is lower than the bedrock channel at the upper end of the controlling canyon. The presence of Elaho basin undoubtedly relates to differential erosion of the bedrock by glacial ice, but the reason for this is unclear; there is no apparent change in the bedrock lithology along the valley bottom (see Roddick *et al.*, 1979). The baselevel of the alluvial reach at present is controlled, not by the bedrock of the canyon, but by bouldery rapids located 1.5 km above the canyon which forms a minor step in the longitudinal profile of the river (Fig. 5). These rapids are the product of a prehistoric

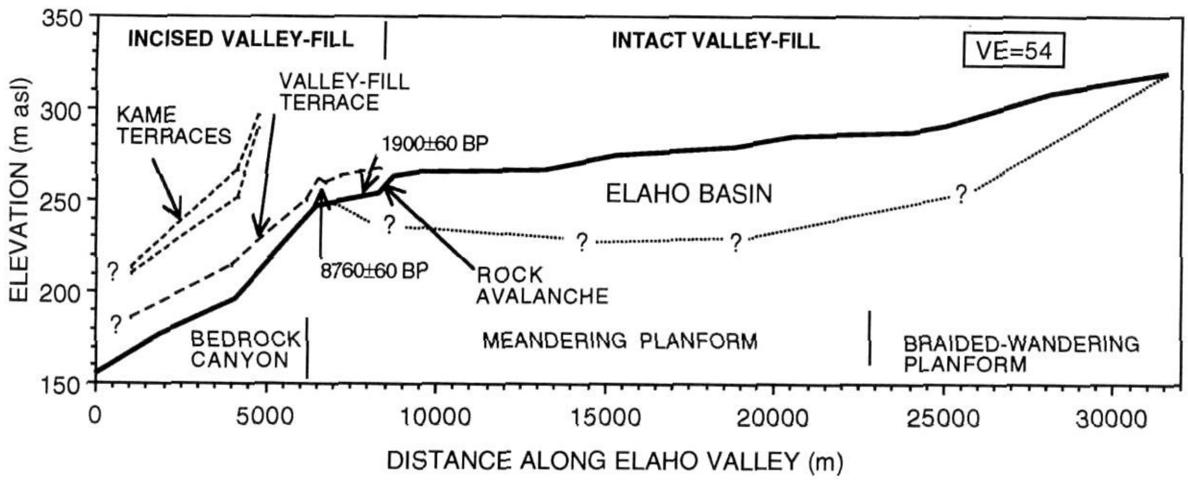

FIGURE 5. The longitudinal profile of Elaho River showing the incised and intact valley-fill deposits and the kame terraces. Note the vertical location of the two radiocarbon dates.

Profil longitudinal de l'Elaho River montrant la section encaissée dans des matériaux de remblaiement non remaniés et les terrasses de kame. Noter la position verticale des deux datations au radiocarbone.

rock avalanche (10^6-10^7 m^3; Jordan, 1987; Brooks, 1992), and form a "natural" division between the incised and unincised reaches of Elaho Valley. (While the rock avalanche raised baselevel perhaps 10 m, it seems unreasonable that this could have initiated aggradation over the entire 23 km long alluvial reach thereby totally obscuring an older incised valley-fill.)

The intact valley-fill of Elaho basin, thus, represents within-valley sediment storage; the unincised morphology precludes it as a RGS source according to the methodology employed in this study. Any glacial sediments directly deposited into Elaho basin likely are preserved beneath the alluvial surface and thus have not contributed RGS to Squamish Valley. It is plausible that aggradation occurred rapidly during or after deglaciation so that RGS derived from further upstream was transported across the alluvial reach, through the lower canyon and into Squamish Valley. But the general lack of remnant glacial deposits from the areas upstream of the alluvial reach, however, suggests that a major portion of the RGS volume exported from Elaho Valley is not being ignored.

The incised valley-fill along the lower canyon occurs as a series of discontinuous terrace surfaces. Altimeter measurements revealed that some of the terraces occur above the intact alluvium of the meandering reach located upstream (Fig. 5). These high terraces are interpreted as kame terraces having formed against glacial ice during deglaciation in the late Pleistocene. They are ignored in the incision calculations because presumably a large portion of the valley bottom was occupied by ice rather than sediment. It is not known how much sediment was deposited against or upon the ice and later exported to Squamish Valley. The terraces situated below the kame terraces are tentatively correlated through the canyon and used in the incision calculations (Fig. 5), but it is not known with certainty that they represent a continuous valley-fill surface because of a lack of dating control.

The volume of incision for Elaho Valley is calculated to be 6×10^6 m^3, based upon 10 cross-valley profiles along the lower canyon reach (Table III). This volume is complicated by two factors: 1) the lack of incised valley-fill deposits over a large portion of the valley and, 2) uncertainty in reconstructing the valley-fill morphology where incised deposits are present. While certainly questionable, the 6×10^6 m^3 volume reflects RGS exported to Squamish Valley based upon the available geomorphic evidence.

Upper Squamish Valley

Upper Squamish Valley is 350 km^2 in area and joins Squamish Valley 56 km upstream of Squamish delta (Fig. 1). The river is 21 km long, originating in the Pemberton ice fields (Fig. 2c). The river flows within a bedrock canyon or upon bedrock except for three short alluvial reaches, the longest being 0.5 km. Canyon depth is variable (Fig. 6), reaching a maximum of about 55 m with the river ranging from "fit" to "underfit" to the canyon width. Dipper Creek occupies the only major tributary valley (Fig. 2c) and flows within a bedrock canyon which attains a maximum depth of 75 m.

Incised valley-fill deposits are present discontinuously along 15 km of upper Squamish River and 5 km of Dipper Creek (Fig. 2c). Along the valley cross-section, the valley-fill terrace is both paired and unpaired; in cross-section, it commonly occurs as a distinct downward break-in-slope to the valley apron deposits rather than as a quasi-flat surface. Although absent along the lower 2 km of the valley, the valley-fill is believed to have once been continuous from the "Little Ice Age" glacial trimline of the Pemberton ice fields to the valley mouth. The thickness of the valley-fill averages 40-50 m from the Neoglacial trimline to about Dipper Creek (Fig. 6). It thickens noticeably at Dipper Creek confluence (Fig. 6), then appears to thin gradually to the valley mouth where it either converges with the Squamish River water surface or is buried beneath postglacial alluvium of the Squamish valley-fill. Backwater deposits attributable to Squamish River impoundments by Mount Cayley debris avalanches are present just beyond the mouth of upper Squamish Valley (Brooks and Hickin, 1991), but not within upper Squamish Valley.

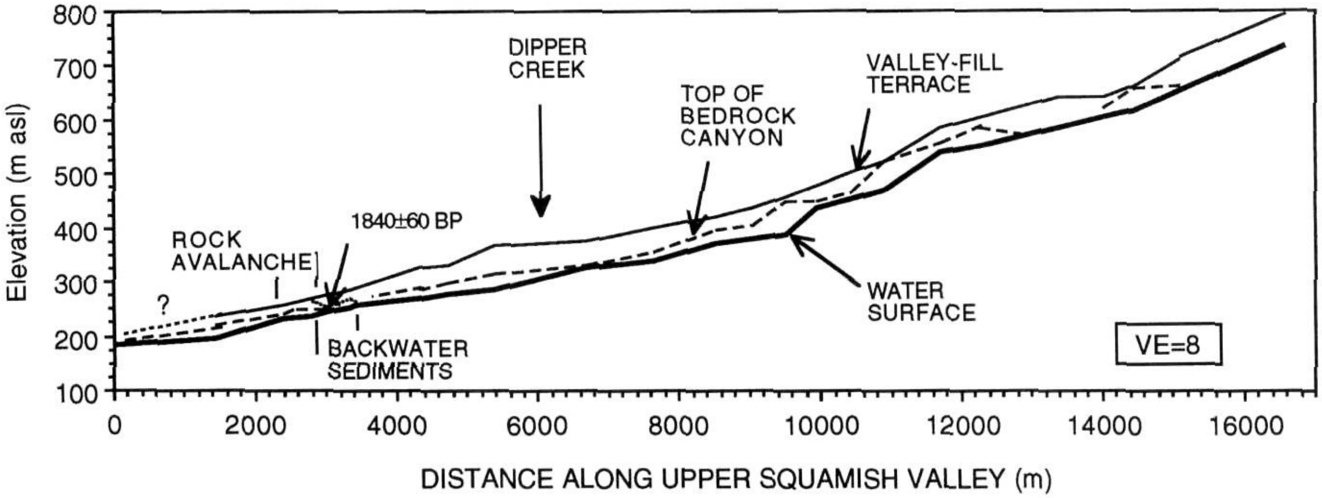

FIGURE 6. The longitudinal profile of upper Squamish River showing the river surface, bedrock surfaces, backwater sediments, and the valley-fill terraces. Note the vertical positions of the 1840 ± 60 BP radiocarbon date within the backwater sediments immediately upstream of the rock avalanche.

Profil longitudinal du cours supérieur de la Squamish River montrant la surface du cours d'eau, la surface de la roche en place, les sédiments des eaux de retenue et les terrasses de matériaux de remblaiement. Noter la position verticale de la datation de 1840 ± 60 BP dans les sédiments des eaux de retenue, immédiatement en amont du glissement rocheux.

Bedrock forming the top of the canyon represents the only major surface between the valley-fill terrace and the river (Fig. 6). It occurs commonly as a quasi-flat surface above a steep-sided canyon or as a distinct break-in-slope at the interface between the top of the bedrock canyon and the overlying unconsolidated valley-fill. Isolated minor erosional(?) terraces are present beneath the valley-fill terrace, but no attempt was made to correlate them.

The valley-fill deposits along upper Squamish Valley consist of glacio-fluvial gravel overlying glacigenic diamicton, representing outwash (and possibly sediments derived from the valley-sides) and till, respectively. Glacio-lacustrine deposits are present in minor isolated pockets, probably relating to minor pondings between ice and the valley sides. All of these deposits presumably formed during the Fraser Glaciation. Since most of upper Squamish River and all of Dipper Creek flow in bedrock canyons, and there are no major secondary terraces below the valley-fill terrace, the storage of postglacial sediments unrelated to the reworking of Fraser Glaciation drift is not a significant factor. Of note, however, backwater sediments occur along a 0.5 km reach of upper Squamish River up to 10 m above the river surface. These accumulated in response to an impoundment caused by a late Holocene rock avalanche 3 km above the valley mouth (Figs. 2c and 6). The backwater deposits represent a comparatively minor deposit along the valley bottom.

The volume of RGS exported from upper Squamish Valley is calculated to be 130 × 10^6 m^3 (Table III), based upon 26 cross-valley profiles along upper Squamish River and 4 along Dipper Creek.

Cheakamus Valley

Cheakamus Valley is 1100 km^2 in area and joins the trunk valley 12 km upstream of Squamish delta (Figs. 1 and 2d). Large ice fields are present within the watershed, but much of the resulting sediment supply is trapped within Cheakamus and Garibaldi lakes (Fig. 2d). Below Cheakamus Lake, Cheakamus River alternates between alluvial and bedrock canyon reaches for 49 km to the river mouth. Above the Squamish-Cheakamus confluence, the alluvial reaches are present along the valley bottom at 0-14 km, 19-24 km and 42-49 km while the canyons occur at 14-19 km and 30-42 km; Daisy Lake is a hydro-electric reservoir located between 24-30 km. The lower alluvial reach represents an extension of the Squamish valley-fill, the baselevel of which is controlled by Cheekye Fan, a debris fan formed of volcanic detritus originating from Mount Garibaldi and transported into Squamish Valley down Cheekye River (see Mathews, 1952). Baselevel of the other two alluvial reaches is controlled by the bedrock of the immediate downstream canyon. Callaghan Creek occupies the only major tributary valley; it flows within a bedrock canyon over its lower 14 km.

Incised valley-fill deposits are strikingly absent from the majority of Cheakamus and Callaghan Valleys. A valley-fill terrace is found only along the alluvial reach immediately below Cheakamus Lake, specifically along the lower 3 km of this reach beginning approximately at the Helm Creek-Cheakamus confluence and extending downstream (hereafter referred to as the "Helm Creek reach"; Fig. 2d). Along the Helm Creek reach, the valley-fill deposit thickens downstream to about 60 m then abruptly terminates (Fig. 7, but see below).

The incised valley-fill is well exposed in a 50 to 60 m high cutbank near the lower end of the Helm Creek reach. The lower four-fifths of the exposure consists of a thick glacigenic diamicton unit overlain by interbedded glacio(?)-fluvial and glacigenic diamicton deposits. Elsewhere, more limited exposures of the valley-fill (several metres in vertical thickness) reveal interbedded diamicton and glacio(?)-fluvial sand and gravel at the top of the terrace and glacigenic diamicton at the river. All of the deposits probably relate to the Fraser Glaciation.

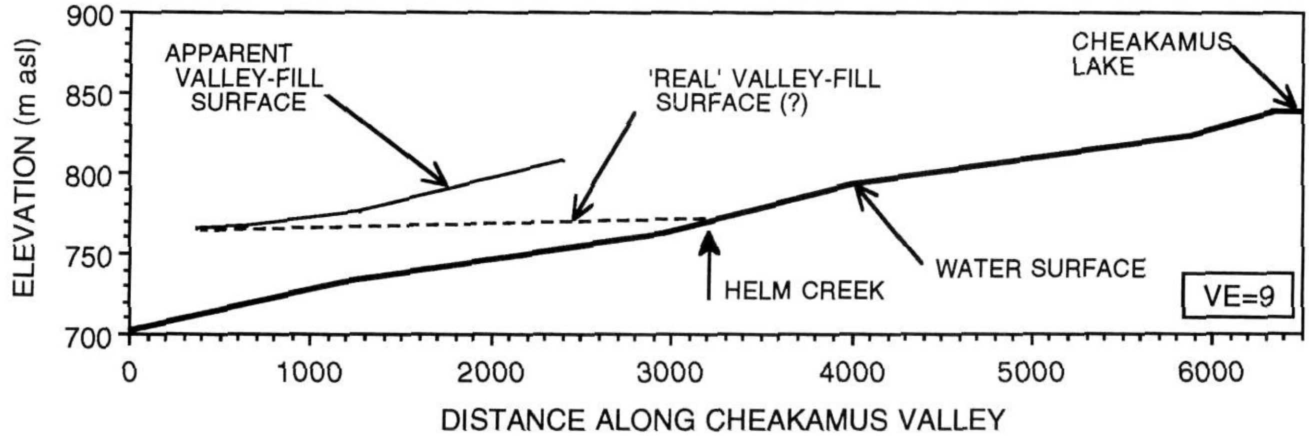

FIGURE 7. The longitudinal profile of the incised valley-fill and the water surface along the Helm Creek Reach in Cheakamus Valley. As is explained in the text, note the erroneous valley-fill measurement causing the discrepancy between the 'real' and 'apparent' valley-fill terrace.

Le profil longitudinal de l'encaissement dans les matériaux de remblaiement et de la surface du cours d'eau le long de la section du Helm Creek, dans la vallée de Cheakamus. Noter que les mesures erronées sur les matériaux de remblaiement sont à l'origine de la différence entre la vraie surface et la surface apparente des matériaux de remblaiement.

The calculation of incised valley-fill volume for Cheakamus Valley is based entirely upon the 3 km long Helm Creek reach. Although field and aerial photograph evidence indicates that the valley-fill terrace thins towards Helm Creek and is absent between Helm Creek confluence and Cheakamus Lake, this trend is not apparent from the altimeter measurements which suggests that it remains thick over the entire reach (Fig. 7). It appears that the upstream-most altimeter measurement did not in fact measure the valley-fill terrace. (The relevant cross-valley profile was situated in first-growth forest making it impossible to relate the measured surface to the "real" valley-fill terrace both upstream and across the valley.) In this particular case, the resulting error probably exceeds that stated in Table II, most likely causing moderate to major error (10-100% overestimation).

Based entirely upon valley-fill incision along the Helm Creek reach, the volume of RGS exported to Squamish Valley is calculated to be 54×10^6 m^3, using four cross-valley profiles (Table III).

Since the incised valley-fill is located 42 km from the valley mouth (Fig. 2d), an interesting problem concerns the possible trapping of RGS within an impoundment of Cheakamus River located 12 km downstream of the Helm Creek reach. This impoundment is caused by the Rubble Creek debris fan which is composed of landslide debris originating from "The Barrier", a large, precipitous cliff of lava that failed several times in the postglacial period (Fig. 2d; Moore and Mathews, 1978; Hardy *et al.*, 1978). For trapping to have occurred, the debris fan must have formed a stable impoundment prior to the complete transfer of RGS downstream. However, the relative timings of these events are not known nor is it clear if a stable impoundment has existed over much of the postglacial period. An impoundment did exist prior to the construction of Daisy Lake dam in the 1950's (Hardy *et al.*, 1978), but this may have persisted only since 1855/56, the time of the last major failure. Tree stumps protruding through the water surface and channel deposits of Cheakamus River adjacent to, and for 5 km downstream of, Rubble Creek debris fan indicate that the pre-1855/56 level of the stream was lower than at present. The proportion of RGS trapped behind the debris fan is not known, but the pre-Daisy Lake dam morphology of the valley bottom suggests that it likely is less than 50% of the RGS volume represented by the incision along the Helm Creek reach.

Mamquam Valley

Mamquam valley is 360 km^2 in area and joins Squamish Valley 5 km upstream of Squamish delta (Fig. 1). The valley extends eastward for 11 km then splits into two arms; one gradually curving to the south that is occupied by Mamquam River, the other curving to the north being wider and representing the morphological trunk valley (Fig. 2e). Drainage over much of the trunk valley is displaced laterally by the Ring Creek lava flow which extends from the Opal Cone on the southern side of Mount Garibaldi down the middle of the valley for 18 km to near the valley mouth (Fig. 2e; see Mathews 1958). The eruption occurred between about 10.7 and 9.3 ka BP (Brooks and Friele, 1992). Streams in the headwaters of the trunk valley drain extensive ice fields on Mount Garibaldi and Mamquam Mountain (Fig. 2e). Mamquam River may be generally divided into three sections: a primarily alluvial reach above the trunk valley, a bedrock canyon adjacent to the lava flow, and an alluvial reach beyond the toe of the lava flow for the remaining distance to Squamish-Mamquam confluence. The channel beds along the alluvial reaches are gravel.

An incised valley-fill deposit exists along a 3 km reach of Mamquam River, beginning near the nose of the lava flow (Fig. 2e). The surface of the valley-fill is paired and terminates abruptly near the valley mouth. It is incised 90 to 60 m. Topset and foreset beds, and a complex mosaic of foreset beds exposed in a road cut to the north of the river and in a gravel pit to the south, respectively, indicate that the valley-fill is a raised delta deposit. As discussed below, the delta formed during deglaciation. Secondary terraces are not present beneath the valley-fill, but aerial photographs that predate the gravel pit show a set of erosional(?) terraces well above the river surface, since destroyed by gravel pit excavations.

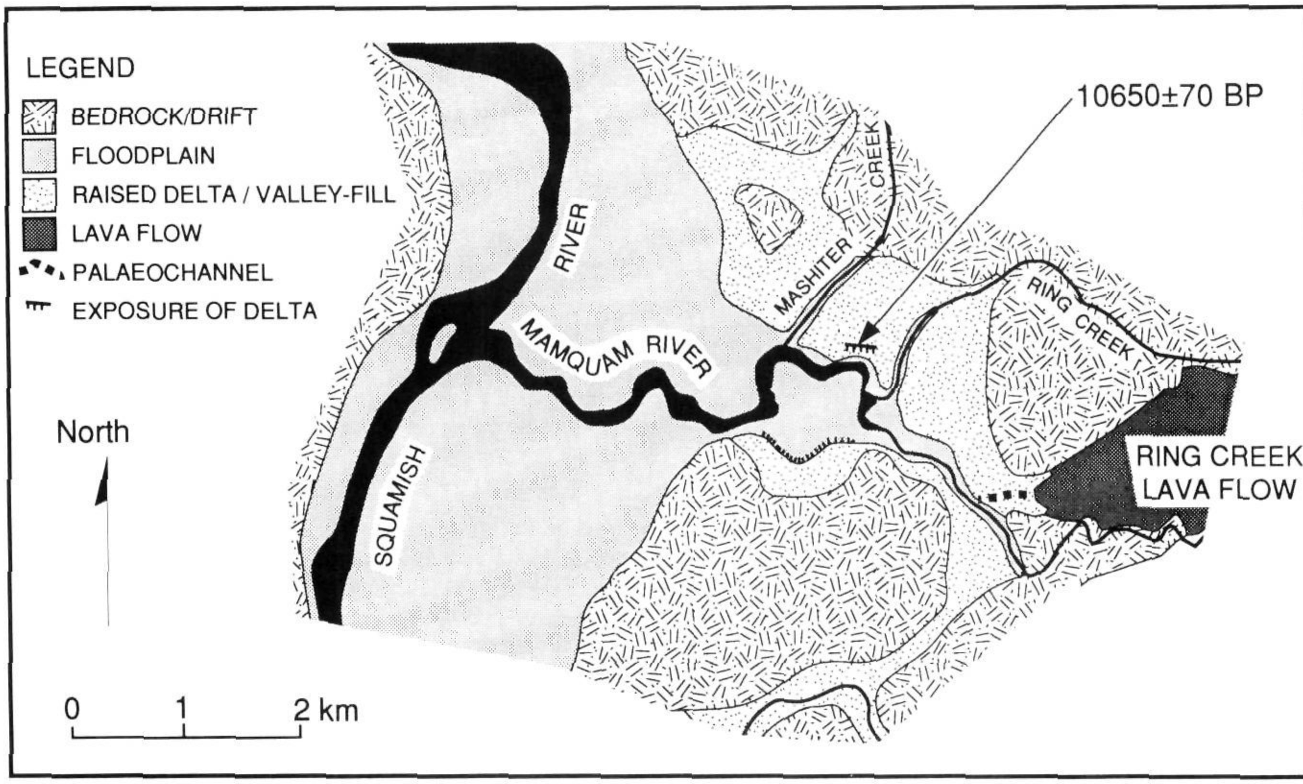

FIGURE 8. The raised delta deposit along the lower end of Manquam Valley in relation to the nose of the Ring Creek lava flow. Note the location of the 10,650 ± 70 BP radiocarbon date.

Les dépôts de delta soulevé le long de la dernière section de la vallée de la Manquam River en relation avec la pointe de la coulée de lave de Ring Creek. Noter la localisation du site de la datation de 10 650 ± 70 BP.

Incorporating incision from elsewhere in the drainage basin into the volume calculations is complicated by the presence of the Ring Creek lava flow. Any incision from the area now covered by the Ring Creek lava flow obviously cannot be measured easily, but geomorphic evidence suggests that this is minimal. Although presently displaced by the lava flow, the drainage network presumably occupied the central part of the valley prior to the extrusion. At the nose of the flow, a small creek flowing upon intact valley-fill deposits (the surface of the raised delta) is underfit within a large channel thought to have been once occupied by ancestral Mamquam River prior to its lateral displacement by the Ring Creek lava flow (Fig. 8). Since the surface of the valley-fill just beyond the nose of the lava flow is not incised, incision of the valley-fill likely occurred after the stream network was displaced by the lava flow. The valley-fill beneath the lava flow, thus, probably is intact (unincised). Along Mamquam River upstream of the Ring Creek lava flow, there is no evidence of an incised valley-fill.

Based entirely upon incision into the deltaic deposits downvalley of the Ring Creek lava flow, the volume of RGS exported to Squamish Valley is calculated to be 130×10^6 m^3 (Table III), determined from four point elevations on the top of the delta and two cross-valley profiles.

TIMING OF THE REWORKED GLACIAL SEDIMENT TRANSFER

The timing of the RGS transfer was evaluated by dating stream incision into the valley-fill deposits. The goal of the dating is to establish two things for each valley: 1) the end of deglaciation, since valley-fill incision probably began at the same time as the proglacial component of the transitional paraglacial period waned and 2) a qualitative assessment of whether valley-fill incision is continuing and, if it has ceased, the time when the major streams attained their present level along the valley bottom (or within several metres of it).

Ashlu Valley

The aggradation of glacio-lacustrine sediments behind an ice impoundment at Pokosha confluence during deglaciation is intrinsically linked to the presence of glacial ice in Ashlu Valley. A maximum date for deglaciation is 11.3 ka BP, the assumed age of the terminal moraine in Howe Sound formed by a valley glacier originating from Squamish Valley that occupied the drainage basin (Mathews *et al.*, 1970). A minimum date was obtained from 24 km above the valley mouth where a piece of reworked wood found within valley-fill/valley apron deposits produced a radiocarbon age of 9920 ± 130 BP (Fig. 2a and Table IV). This date indicates that trees were growing along the valley bottom and/or sides with the ice probably near or at its present position within Ashlu Valley before 9.9 ka BP. It thus seems reasonable that the ice dam at Pokosha confluence had failed and that incision in the lower part of the valley had begun before the upper section of the valley became deglaciated and the 9920 ± 130 BP tree began to grow. Valley-fill incision in Ashlu Valley likely began between 11-9.9 ka BP.

TABLE IV

Radiocarbon dates relevant to deglaciation and stream incision

Laboratory Number	Age (years BP)	Material	Valley	Coordinates
SFU 683	9920 ± 130	wood fragment	Ashlu Valley	50°01.6'N 123°34.7'W[a]
SFU 714	2120 ± 70	wood fragment	Ashlu Valley	50°01.5'N 123°34.3'W[a]
SFU 691	4150 ± 70	peat	Ashlu Valley	49°55.1'N 123°23.1'W[b]
TO 1644	8760 ± 60	charcoal	Elaho Valley	50°08.0'N 123°28.7'W[c]
SFU 708	1900 ± 60	wood fragment	Elaho Valley	50°08.5'N 123°29.8'W[c]
SFU 682	1840 ± 60	sapling stalk	upper Squamish Valley	50°09.2'N 123°24.2'W[c]
Beta 43865	10650 ± 70	tree slump	Mamquam Valley	49°43.9'N 123°05.3'W[d]

[a] these coordinates are on NTS map 92J/4 entitled "Princess Louisa Inlet".
[b] these coordinates are on NTS map 92G/14 entitled "Cheakamus River".
[c] these coordinates are on NTS map 92J/3 entitled "Brandywine Falls".
[d] these coordinates are on NTS map 92G/10 entitled "Pitt River".

Along their courses through incised valley-fill deposits, the morphology of Ashlu, Pokosha and Tatlow creeks varies between bedrock canyon and bedrock-controlled alluvial reaches indicating that valley-fill incision has either ceased or is occurring at a very slow rate reflecting fluvial incision of bedrock. A minimum date for the cessation of incision was obtained from just below Pokosha confluence where a peat bog is situated upon a terrace about 6 m above the present Ashlu Creek water surface. A core revealed that the bog consists of peat overlying organic-rich sand; a composite sample from the base of peat (80-85 cm depth) produced a radiocarbon age of 4150 ± 70 BP (Table IV). The dated peat provides a minimum age for the terrace surface. Since this surface is located about 60 m below the valley fill terrace (Fig. 4), the vast majority of incision occurred prior to 4.2 ka BP.

A second date relating to valley-fill incision was obtained from a contemporary flood plain deposit located 26 km above the valley mouth (Figs. 2a and 3). Here the river meanders along a confined reach excavated into the valley-fill. The reach appears to be equilibriated to local baselevel with the contemporary flood plain deposits forming a 2 m high quasi-flat bench parallel to the water surface. At a cutbank, a partially decomposed tree branch contained within interbedded sands and peat about 150 cm below the flood plain surface produced a radiocarbon age of 2120 ± 70 BP (Table IV). Although the branch probably is reworked, the general abundance of organic materials within the cutbank suggests that it is of local origin and thus reflects the age of the encapsulating deposits. Along this reach, Ashlu Creek appears to have became stabilized prior to 2.1 ka BP, a minimum date more reflective of the flood plain age than the end of incision. The 2120 ± 70 BP date, however, is believed to be less representative of the overall cessation of incision in Ashlu Valley than the 4150 ± 70 BP radiocarbon age obtained from the downstream end of the incised valley-fill.

In Ashlu Valley, valley-fill incision began between 11-9.9 ka BP and probably ceased prior to 4.2 ka BP.

Elaho Valley

No datable organic material relevant to deglaciation was found in Elaho Valley. The end of deglaciation presumably happened at a similar time as Ashlu Valley, occurring between 11-9.9 ka BP. The initiation of valley-fill incision probably also began at this time as the proglacial component waned to reflect the extent of the postglacial ice fields in Elaho Valley.

The bedrock canyon morphology of Elaho River along the reach of incised valley-fill indicates that incision has ceased. A date related to fluvial activity upon an erosional terrace at the upstream end of the canyon was obtained from a discontinuous charcoal layer contained within overbank sands that overlie channel gravel (Figs. 2b and 5). A single charcoal fragment produced a radiocarbon age of 8760 ± 60 BP, a maximum age for the sand (Table IV). The relationship of the 8760 ± 60 BP charcoal to the exact vertical position of the river is not known. It seems reasonable that Elaho River was somewhat above its present level when the charcoal layer was deposited and thus was incising actively into the valley fill deposits at 8.8 ka BP.

The end of the RGS transfer to Squamish Valley would have occurred when Elaho River had removed the valley-fill deposits from the lower canyon. A related date was obtained from an alluvial deposit immediately above the canyon at the upstream end of the incised valley-fill (Figs. 2b and 5). Here a wood fragment buried beneath contemporary flood plain deposits produced a radiocarbon age of 1900 ± 60 BP (Table IV). The wood appears to have been deposited upon a channel bar that later became incorporated into the flood plain; therefore, 1900 ± 60 years BP represents a maximum age for the overlying flood plain deposits. Assuming the age of the wood reflects that of the channel bar within the flood plain, 1.9 ka BP represents a minimum age for the end of stream incision since the river attained this level before the wood was deposited.

Valley-fill incision in Elaho Valley probably began between 11-9.9 ka BP, was on-going at 8.8 ka BP, and ceased prior to 1.9 ka BP.

Upper Squamish Valley

Determining the initiation of valley-fill incision in upper Squamish Valley is hampered by the lack of relevant organic materials in the valley deposits and also by the lack of alluvial terraces. The end of deglaciation presumably happened at a similar time as Ashlu Valley, occurring between 11-9.9 ka BP. The initiation of valley-fill incision probably also began at this time as the proglacial component waned to reflect the extent of the postglacial ice fields in upper Squamish Valley.

The predominantly bedrock canyon morphologies of upper Squamish River and Dipper Creek indicate clearly that valley-fill incision has ceased. A minimum date relating to this cessation was obtained from backwater sediments formed within a river impoundment caused by a postglacial rock avalanche (10^6-10^7 m^3; Jordan, 1987; Brooks, 1992) located 3 km from the valley mouth (Figs. 2c and 6). A sapling stalk contained within lacustrine sediments and believed to have been killed by this impoundment, produced a radiocarbon age of 1840 ± 60 BP (Table IV). The tree stalk grew upon the terrace as a part of a palaeosurface situated about 7 m above the present river surface and about 22 m below the valley-fill terrace. Since backwater sediments locally extend to within 2-3 m of the present river surface, the river was at, or close to, its present vertical position at 1.9 ka BP. The radiocarbon age, thus, represents a minimum date for the cessation of incision. Since the date was obtained from the lower section of the valley, stream incision throughout upper Squamish Valley probably ceased before 1.9 ka BP.

Valley-fill incision in upper Squamish Valley probably began between 11-9.9 ka BP and ended before 1.9 ka BP.

Cheakamus Valley

No radiocarbon dates were obtained or have been published relating to deglaciation of Cheakamus Valley or to valley-fill incision of the Helm Creek reach. The end of deglaciation presumably happened at a similar time as Ashlu Valley, occurring between 11-9.9 ka BP. The initiation of valley-fill incision probably also began at this time as the proglacial component waned to reflect the extent of the postglacial ice fields in Cheakamus Valley. The wide contemporary flood plain of Cheakamus River along the Helm Creek reach is controlled by a bedrock canyon suggesting that incision has stabilized with lateral channel migration being the dominant contemporary process. Incision presumably ceased several thousand years ago if it was consistent with the other major tributary valleys.

Mamquam Valley

In Mamquam Valley, the incised valley-fill is formed by a raised deltaic deposit. Incision into this deposit was controlled by deglacial-postglacial sea level fluctuations although the initial baselevel of about 100 m asl may have been formed by an ice marginal lake (Mathews, 1952). The delta was prograding actively at about 10.7 ka BP as indicated by an *in situ* tree stump aged 10,650 ± 70 BP sited within topset beds about 20 m below the surface of the delta (Fig. 8 and Table IV). Subsequent isostatic uplift caused sea level to fall, initiating valley-fill incision. As incision into the delta extends only 3 km upvalley, it probably kept pace with the sea level fall although channel armouring may have slowed the downcutting. Sea level reached its postglacial minimum (−12 m asl) at roughly 9 ka BP, rising to its present level by 5 ka BP. At present, baselevel of Mamquam River is almost certainly equilibriated, therefore, incision has effectively ceased.

Valley-fill incision in Mamquam Valley began after about 10.7 ka BP and likely ceased about 9 ka BP or shortly thereafter.

DISCUSSION

CONTROLS UPON THE REWORKED GLACIAL SEDIMENT VOLUMES

The volume of RGS exported to Squamish Valley from a particular valley depends upon the amount of glacial deposits stored in the valley bottom that is accessible to the river network. The most important factors concerning this are local valley morphology and late Quaternary history. For example, Elaho Valley is the largest tributary watershed in the drainage basin, but contains a large within-valley sediment trap where glacial (and postglacial) sediments likely are stored within a bedrock controlled sedimentary basin. Because of this valley morphology, only a very small portion of Elaho Valley has contributed to the export of RGS, and in consequence, the RGS volume is relatively low (Table III). In contrast, the late Quaternary history of Mamquam Valley has left thick valley-fill deposits that accumulated at the valley mouth as part of a delta graded to a high deglacial baselevel. This feature subsequently was eroded early in the postglacial period when baselevel fell. The importance of historical conditioning is further reinforced by the fact that valley-fill deposits in Mamquam Valley are preserved beneath the Ring Creek lava flow, otherwise the volume of exported RGS would be even larger.

TIMING OF THE REWORKED GLACIAL SEDIMENT TRANSFER

In all of the major tributary valleys, stream incision into the valley-fill deposits appears to have ceased thousands of years ago although there is no reason to believe that the cessation of incision between the valleys has been synchronous. For example, the dates and geomorphic evidence from Mamquam and Ashlu valleys indicate that incision ceased in the early and middle Holocene, respectively. The cessation of incision likely is specific to an individual valley and dependent upon a wide range of factors such as postglacial sediment flux and discharge regime, postglacial baselevel control and composition of the valley-fill.

While vertical incision may cease, the export of glacial materials from a watershed never totally stops so long as Fraser Glaciation drift remains in the landscape. Despite becoming generally inaccessible to a river system, drift invariably is introduced by mechanisms such as debris slumps along the lower valley-sides and cutbank erosion where a stream abuts against remnant valley-fill deposits. The occurrence of natural exposures of glacial deposits in all the tributary valleys attests to continuing erosion. Thus, the export of RGS to Squamish Valley appears to be continuing at a very low residual rate reflecting this erosion, but the bulk of the transfer occurred thousands of years ago as suggested by the cessation of the stream incision.

RELATIVE IMPORTANCE OF REWORKED GLACIAL SEDIMENT TO LONG TERM STORAGE OF SEDIMENT WITHIN SQUAMISH VALLEY

The combined volume of RGS derived from the major tributary valleys is 415 × 10^6 m^3 (Table III) This material is stored within Squamish valley-fill in addition to Holocene and late Pleistocene sediments of other origins. Ideally, the relative importance of RGS to the long term storage of sediment within Squamish Valley should be determined by comparison with the total volume of Squamish valley-fill and to its individual components. Unfortunately, this information is not available since there has been no subsurface survey of Squamish Valley.

The best available means of assessing the relative importance of RGS to the Squamish valley-fill is by comparing it to the contemporary sediment flux at Squamish delta. Hickin (1989) examined 1930, 1973 and 1984 bathymetric survey charts of Howe Sound and found that the contemporary sediment flux to the delta is $1.29 \times 10^6\ m^3a^{-1}$ which causes the delta to prograde into Howe Sound at the rate of 3.86 ma^{-1}. The sediment flux to the delta reflects contemporary sediment supply within Squamish River drainage basin and primarily is the result of "normal" denudational processes in the southern Coast Mountains since the transfer of RGS appears to continue only at a very low residual level. The most important sediment sources probably are alpine glaciers and mass movements from Mount Cayley and Mount Garibaldi, Quaternary volcanoes of the Garibaldi Volcanic Belt. The combined volume of RGS represent only 321 ± 161 years of contemporary sediment flux, the $\pm 50\%$ error reflects the order of magnitude character of the RGS volumes.

Although the applicability of the $1.29 \times 10^6\ m^3a^{-1}$ rate over the postglacial timescale obviously is not known, it seems that the amount of material derived from only "normal" denudational processes far exceeds that of the total volume of RGS especially considering that the former has been on-going over the entire postglacial period. RGS, thus, appears to represent only a small component of the postglacial sediment stored in Squamish Valley. The importance of "normal" denudational processes is further exemplified by the fact that a debris avalanche from Mount Cayley occurring at 4.8 ka BP almost instantaneously delivered $200 \times 10^6\ m^3$ of material to Squamish Valley (Evans and Brooks, 1991) which exceeded the individual RGS volume from every major tributary valley. Mount Garibaldi has also experienced major deglacial and postglacial slope failures with a large portion of this material reaching Squamish Valley (Mathews, 1952; Jordan, 1987).

Squamish delta is located at the lower end of the 56 km long Squamish valley-fill. In an attempt to reconstruct the downvalley advancement of the delta front, Hickin (1989) extrapolated the 3.86 ma^{-1} progradation rate back into the late and middle Holocene. Based upon a rectangular profile defined by valley width obtained from 1:50,000 scale NTS topographic maps and a uniform depth of 250 m, the delta front appears to have been about 8 km upvalley at 3000 ± 875 years and a further 10 km upvalley at 6000 ± 1500 years. Using the same rectangular profile, the subtraction of the combined RGS volume results only in a roughly 2 km upvalley translation of the present delta front.

The reworked glacial component of transitional paraglacial sedimentation appears to be a relatively minor part of the Squamish valley-fill and a small portion of the postglacial sediments stored in the Squamish Valley.

APPLICABILITY TO OTHER WATERSHEDS

The major tributary valleys of this study range in area from 290 to 1250 km^2. This suggests that the bulk of RGS transfer also has ended in other similar-sized watersheds in southwestern British Columbia. This premise may be extended to the 3600 km^2 Squamish River drainage basin, but not without qualification. At this scale, sediment storage in Squamish Valley occurs as an intact (unincised) valley-fill, but it could become subject to incision through, for example, tectonic uplift or a major drop in sea level. It would appear that if the RGS transfer is still important in the present landscape of British Columbia as suggested by Church *et al.* (1989) and Church and Slaymaker (1989), then it is occurring at drainage basin scales greater than that of the major tributary valleys and possibly larger than that of Squamish River.

The importance of the very low residual RGS transfer appears to be small relative to the contemporary sediment supply into Squamish Valley. This in part reflects the low accessibility of the remnant glacial deposits to the river network, but also the comparatively high sediment supply from other "normal" denudational processes operating in the local landscape. In another geomorphic setting where remnant glacial deposits remain accessible to streams through, for example, lateral channel migration, it is possible that a continuing RGS transfer is important to the contemporary sediment supply regime (see Church and Slaymaker, 1989; Church *et al.*, 1989). An obvious setting for the continuing influence of the transfer of RGS would be in watersheds that contained large lakes during deglaciation which resulted in the storage of large quantities of glacio-lacustrine and glaciofluvial sediments.

An obvious question concerns whether the major tributary valleys of the Squamish drainage basin are representative of other similar-sized watersheds in southwestern British Columbia. There is no doubt that Mamquam Valley, where the Ring Creek lava flow has buried a large proportion of the valley-fill, is hardly typical. The other valleys, however, do not seem to be particularly unique. For example, thick valley-fill deposits and large within-valley sediment traps (lakes) are present in other drainage systems. Any question of representativeness surely reinforces the importance of local late Quaternary history and valley morphology as important controls upon the export of RGS.

RGS appears to represent a minor component of the postglacial sediments stored in Squamish Valley. With consideration to the importance of local valley morphology and late Quaternary history, this circumstance probably is not unique to the Squamish River drainage basin. In Squamish River drainage basin, the total volume of RGS does not seem to be severely limited by any atypical controls. The only unusual control that significantly limits the total volume of RGS is the preservation of valley-fill within Mamquam Valley beneath Ring Creek lava flow. While the lava flow undoubtedly has prevented stream incision over a significant area of the valley bottom, it seems unreasonable that a massive augmentation to the total RGS volume in Squamish Valley would have occurred had erosion proceeded (*i.e.*, an order of magnitude increase). For example, a four-fold increase in the Mamquam Valley RGS volume would cause only a doubling of the total RGS volume — not enough to justify changing the original conclusion. The total volume of RGS transferred to Squamish Valley, thus, is not believed to be anomalously low.

Further to this point, the contemporary sediment flux at the delta, upon which the assessment of the total RGS volume is based, warrants consideration because it may be anomalously high, the result of unique sediment sources in the Squamish River watershed. The major sediment sources producing the contemporary sediment flux probably are mass movements from the Mount Garibaldi and Mount Cayley volcanic centres and alpine glaciers. The relative contribution of the mass movement and glacial sources is not known. Alpine glaciers are common in the Coast Mountains and can reasonably be expected to have important sediment contribution in other river systems. The relative importance of this sediment source, all things being equal, probably is proportional to the ice cover within a given watershed. Alpine glaciers cover about 11% of the Squamish River drainage basin, the sediment contribution from which probably is typical of watersheds with similar ice coverage.

Volcanic centres experiencing large scale mass movements are not unique to Squamish River drainage basin (*e.g.*, Lillooet River drainage basin; see Jordan and Slaymaker, 1991), but are not common in other Coast Mountain river systems. However, the volcanic contribution to the contemporary sediment flux at the delta may be less than that from the alpine glaciers, perhaps significantly less. While both volcanoes have experienced mass movement activities in the past 100 years (see Clague and Souther, 1982; Jordan, 1987; Cruden and Lu, 1992), these are relatively small compared to those of the more distant past (see Hungr and Skermer, 1992; Evans and Brooks, 1991). Although causing a high instantaneous delivery of sediment to Squamish Valley, some of which will eventually reach Squamish delta, the rate of delivery is not momentous when averaged over time spans reflecting the intervening periods between mass movements. Also, a significant amount of the landslide debris remains stored within the debris fans rather than being transported to the delta and is not incorporated into the contemporary sediment flux. The contemporary sediment flux likely is "high" because of the mass movement contribution, but probably is not excessively high. Evidence from Squamish Valley, thus, suggests that RGS may form a minor component of the postglacial sediments stored within the trunk valleys of other Coast Mountain river systems.

CONCLUSIONS

RGS have been derived primarily through stream incision into valley-fill deposits in the major tributary valleys of Squamish River drainage basin. As reflected by the volume of incision into the valley-fill deposits, the amount of RGS transferred to Squamish Valley varies considerably between major tributary valley, ranging from 6 to 130 $\times$ 10^6 m^3. The controls upon the amount of material derived from individual tributary valleys are valley morphology and late Quaternary history.

The combined volume of RGS transferred into Squamish Valley is 415 $\times$ 10^6 m^3. This material appears to represent a minor portion of the Squamish valley-fill and a small component of the postglacial sediments stored in Squamish Valley.

Valley-fill incision in the tributary valleys appears to have ceased since the major streams flow within canyons or bedrock-controlled alluvial reaches. Dating indicates that this incision ceased thousands of years ago. Minor erosion of the valley-fill deposits occurs through lateral channel migration and slope instability indicating that the transfer of RGS to Squamish Valley continues at a very low residual rate. This continuation forms a minor component of the contemporary sediment regime of Squamish River.

ACKNOWLEDGMENTS

This work represents part of a Ph.D. dissertation completed at Simon Fraser University under the supervision of E.J. Hickin and forms a component of an ongoing project on the morphodynamics of Coast Mountain rivers funded by the Natural Sciences and Engineering Research Council of Canada (operating grant GP 8376). The manuscript has been improved substantially from reviews by M. Church, J. Desloges and O. Slaymaker, their efforts are sincerely appreciated. Assistance in the field was ably provided by G. Schnare, R. Atkins, M. Gawehns and M. Hafer. I thank the Empire Logging Division of Weldwood Canada and Triple "C" Logging for providing unlimited access to their logging roads. I would also like to thank Mr. and Mrs. Eluck who generously allowed their Squamish Valley cabin to serve as a field headquarters for this study.

REFERENCES

Armstrong, J. E., 1981. Post-Vashon Wisconsin Glaciation, Fraser Lowland, British Columbia. Geological Survey of Canada Bulletin 322, 34 p.

BC Hydro, 1983. Elaho River hydroeletric development, 1982 geotechnical investigations (overview). Hydroelectric Generation Projects Division, Geotechnical Department, April 1983, Report N° Geo 2/83.

Brierley, G. J., 1989. The character of channel planform control on the morphology and sedimentology of the gravel-bed Squamish River flood plain, British Columbia. Ph.D. thesis, Simon Fraser University, 304 p.

Brooks, G. R., 1992. Aspects of post-glacial sediment supply and its control upon the morphology of Squamish River, southwestern British Columbia. Ph.D. Thesis, Simon Fraser University, 448 p.

Brooks, G. R. and Friele, P. A., 1992. Bracketing ages for the formation of the Ring Creek lava flow, Garibaldi Volcanic Belt, southwestern British Columbia. Canadian Journal of Earth Sciences, 29: 2425-2428.

Brooks, G. R. and Hickin, E. J., 1991. Debris avalanche impoundments of Squamish River, Mount Cayley area, southwestern British Columbia. Canadian Journal of Earth Science, 28: 1375-1385.

Church, M., 1983. Patterns of instability in a wandering gravel-bed channel. *In* J.D. Collinson and J. Lewin, eds., Modern and Ancient Fluvial Systems. International Association of Sedimentologists, Special Publication 6: 251-266.

Church, M. and Ryder, J. M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. Geological Society of America Bulletin, 83: 3059-3072.

——— 1989. Sedimentology and clast fabric of subaerial debris flow facies in a glacially-influenced alluvial fan — a discussion. Sedimentary Geology, 65: 195-196.

Church, M. and Slaymaker, O., 1989. Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature, 337: 452-454.

Church, M., Kellerhals, R. and Day, T. J., 1989. Regional clastic sediment yield in British Columbia. Canadian Journal of Earth Sciences, 26: 31-45.

Clague, J. J., 1981. Late Quaternary geology and geochronology of British Columbia, part 2: Summary and discussion of radiocarbon-dated Quaternary history. Geological Society of Canada, Paper 80-35, 41 p.

——— 1986. The Quaternary stratigraphic record of British Columbia: Evidence for episodic sedimentation and erosion controlled by glaciation. Canadian Journal of Earth Sciences, 23: 885-894.

Clague, J. J. and Souther, J. G., 1982. The Dusty Creek landslide on Mount Cayley, British Columbia. Canadian Journal of Earth Sciences, 19: 524-539.

Clague, J. J., Harper, J. R., Hebda, R. J. and Howes, D. E., 1982. Late Quaternary sea levels and crustal movements, coastal British Columbia. Canadian Journal of Earth Sciences, 19: 597-618.

Cruden, D. M. and Lu, Z., 1992. The rockslide and debris flow from Mount Cayley, B. C., in June 1984. Canadian Geotechnical Journal, 29: 614-626.

Day, T. J., 1989. River processes, p. 595-604. *In* R. J., Fulton, *ed.*, Quaternary Geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, No. 1 (*also* Geological Society of America, The Geology of North America, Volume K-l), 839 p.

Desloges, J. R. and Ryder, J. M., 1990. Late Neoglacial history of the Bella Coola region, British Columbia. Canadian Joumal of Earth Sciences, 27: 281-290.

Duford, J. M. and Osbome, G. D., 1978. Holocene and latest Pleistocene cirque glaciation in the Shuswap Highlands, British Columbia. Canadian Journal of Earth Sciences, 15: 865-873.

Evans, S. G. and Brooks, G. R., 1991. Prehistoric debris avalanches from Mount Cayley volcano, British Columbia. Canadian Journal of Earth Sciences, 28: 1365-1374.

Eyles, N. and Kocsis, S. P., 1988. Sedimentology and clast fabric of subaerial debris flow facies in a glacially-influenced alluvial fan. Sedimentary Geology, 59: 15-28.

Eyles, N. and Kocsis, S. P., 1989. Reply to M. Church and J. M. Ryder's discussion of "Sedimentology and clast fabric of subaerial debris flow facies in a glacially-influenced alluvial fan". Sedimentary Geology, 65: 197-198.

Green, N. L., Armstrong, R. L., Harakal, J. E., Souther, J. C. and Read, P. B., 1988. Eruptive history and K-Ar geochronology of the Late Cenozoic Garibaldi Volcanic Belt, southern British Columbia. Geological Society of America Bulletin, 100: 563-579.

Hardy, R. M., Morgenstern, N. R. and Patton, F. D., 1978. The Garibaldi advisory panel, part II — Background studies accompanying general report to the Deputy Minister. British Columbia Department of Highways, 170 p.

Hickin, E. J., 1989. Contemporary Squamish River sediment flux to Howe Sound, British Columbia. Canadian Joumal of Earth Sciences, 26: 1953-1963.

Holland, S.S., 1964 (reprinted 1976). Landforms of British Columbia: A physiographic outline. British Columbia Department of Mines and Petroleum Resources, Bulletin 48, 138 p.

Hungr, O. and Skermer, N. A., 1992. Technical tour N° 1 — debris torrents and rockslides, Howe Sound to Whistler corridor, p. 5-46. *In* Technical tours guidebook. May 7, 1992, Geotechnique and natural hazards symposium, Vancouver, British Columbia, 119 p.

Jackson, L. E., 1987. Debris flow hazard in the Canadian Rocky Mountains. Geological Survey of Canada, Paper 86-11, 20 p.

Jackson, L. E., MacDonald, G. M. and Wilson, M. C., 1982. Paraglacial origin for terraced river sediments in Bow Valley, Alberta. Canadian Journal of Earth Sciences, 19: 2219-2231.

Jordan, P., 1987. Impacts of mass movement events on rivers in the southern Coast Mountains, British Columbia: Summary report. Water Resources Branch, Environment Canada, IWD-HQ-WRB-55-87-3, 62 p.

Jordan, P. and Slaymaker, O., 1991. Holocene sediment production in the Lillooet River basin, British Columbia: A sediment budget approach. Géographie physique et Quaternaire, 45: 45-57.

Leonard, E. M., 1985. Glaciological and climatic controls on lake sediments, Canadian Rocky Mountains. Zeitschrift für Gletcherkunde und Glazialgeologie, 21: 35-42.

——— 1986a. Use of lacustrine sedimentary sequences as indicators of Holocene glacial history, Banff National Park, Alberta, Canada. Quaternary Research, 26: 218-231.

——— 1986b. Varve studies at Hector Lake, Alberta, Canada, and the relationship between glacial activity and sedimentation. Quaternary Research, 25: 199-214.

Luckman, B. H. and Osborne, G. D., 1979. Holocene glacier fluctuations in the middle Canadian Rocky Mountains. Quaternary Research, 11: 52-77.

Mathews, W. H., 1952. Mount Garibaldi, a supraglacial Pleistocene volcano in southwestern British Columbia. American Joumal of Science, 250: 553-565.

——— 1958. Geology of the Mount Garibaldi map-area, southwestern British Columbia, Canada. II. Geomorphology and Quatemary volcanics. Geological Society of America Bulletin, 96: 179-198.

Mathews, W. H., Fyles, J. G. and Nasmith, H. W., 1970. Postglacial crustal movements in southwestern British Columbia and adjacent Washington State. Canadian Joumal of Earth Sciences, 7: 690-702.

Moore, D. P. and Mathews, W. H., 1978. The Rubble Creek landslide, southwestern British Columbia. Canadian Journal of Earth Sciences, 15: 1039-1052.

Ritter, D. F. and Ten Brink, N. W., 1986. Alluvial fan development and the glacial-glaciofluvial cycle, Nenana Valley, Alaska. Journal of Geology, 94: 613-625.

Roddick, J. M., Muller, J. E. and Okulitch, A. V., 1979. Fraser River, British Columbia — Washington. Geological Survey of Canada Map 1386A, Sheet 92, 1:1,000,000 Scale.

Ryder, J. M., 1971a. The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia. Canadian Journal of Earth Sciences, 8: 279-298.

——— 1971b. Some aspects of the morphology of paraglacial alluvial fans in south-central British Columbia. Canadian Journal of Earth Sciences, 8: 1252-1264.

——— 1981. Geomorphology of the southern part of the Coast Mountains of British Columbia. Zeitschrift für Geomorphologie N. F., 37: 120-147.

——— 1987. Neoglacial history of the Stikine-Iskut area, northern Coast Mountains, British Columbia. Canadian Journal of Earth Sciences, 24: 1294-1301.

Ryder, J. M. and Clague, J. J., 1989. British Columbia (Quaternary stratigraphy and history, Cordilleran Ice Sheet), p. 48-58. *In* R. J., Fulton, ed., Quaternary Geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, No. 1 (*also* Geological Society of America, The Geology of North America, Volume K-l), 839 p.

Ryder, J. M. and Thomson, B., 1986. Neoglaciation in the southern Coast Mountains of British Columbia: Chronology prior to the late Neoglacial maximum. Canadian Journal of Earth Sciences, 23: 273-287.

Williams, H. F. L. and Roberts M. C., 1989. Holocene sea-level change and delta growth: Fraser River delta, British Columbia. Canadian Journal of Earth Sciences, 26: 1657-1666.